



Solar Powered Aircraft, Photovoltaic Array/Battery System Tabletop Demonstration Design and Operation Manual

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Introduction

A system was constructed to demonstrate the power system operation of a solar powered aircraft. The system consists of a photovoltaic (PV) array, a charge controller, a battery, an electric motor and propeller. A diagram of this system is shown in figure 1. The system collects energy from the PV array and either utilizes this energy to operate an electric motor or stores it in a rechargeable battery for future use. The system has a control panel which displays the output of the array and battery as well as the total current going to the electric motor. The control panel also has a means for adjusting the output to the motor to control its speed. The entire system is regulated around 12 VDC.

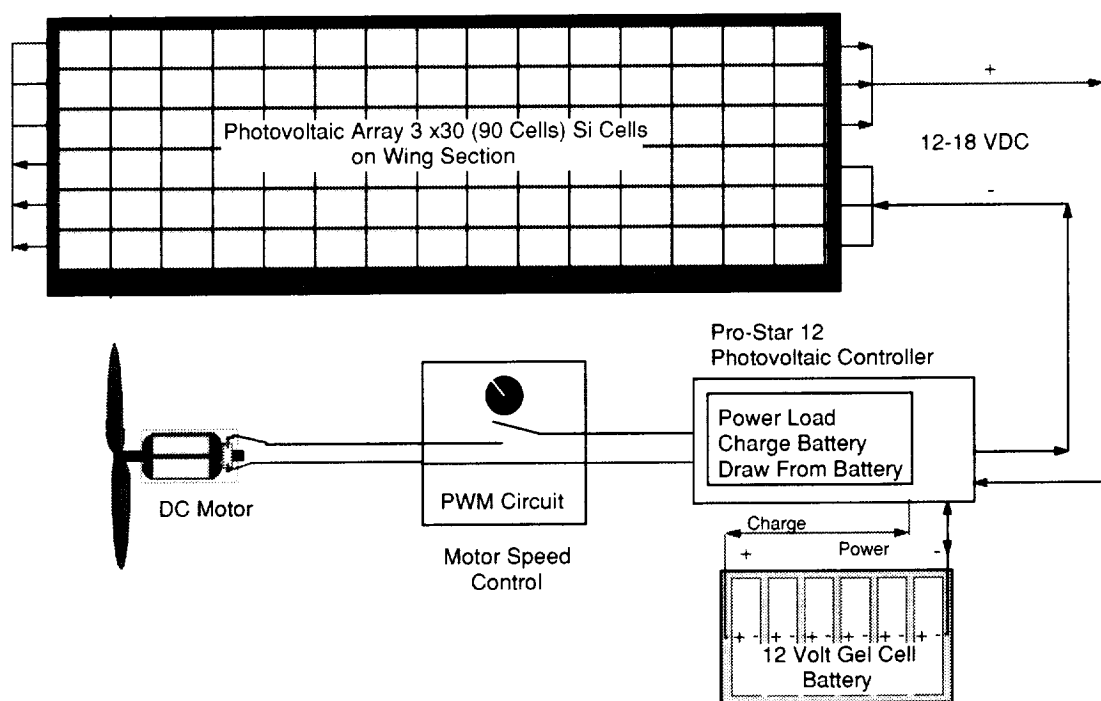


Figure 1 Power System Diagram

PV Array

A PV (Photovoltaic) array is a grouping of solar cells. Solar cells produce electrical power when illuminated. The amount of power varies with the amount of light hitting the cells. Connecting cells into an array is much like connecting batteries. When in series, or wired top to bottom, cell voltages add. When in parallel, or wired side by side, currents add. By connecting cells in series and parallel, any voltage and current can

be achieved. The electrical symbol for a solar cell is a diode, which is its closest match. Without illumination it behaves exactly like a diode.

The PV array consists of 90 silicon solar cells. Each cell is 3.5 cm by 6 cm and has a maximum power output of .52 volts and .56 amps under bright sunlight ($>1000 \text{ W/m}^2$, sunlight at noon on a bright sunny day). An output power curve for each of the solar cells is shown in figure 2. The cells are grouped into 3 strings of 30 cells each. The cell output varies by several parameters; a few of which are, amount of sunlight, cell area, and type of cell material. The amount of light on a cell is directly proportional to the power out of the cell. Double the light intensity and double the power (this does not stay linear at high concentration $>100 \text{ X}$). The current out of the cell is a function of cell area. Increase the area and you will increase the current. The cell material determines the nominal cell voltage. Silicon cells have an output voltage of around .6 volts. All of these parameters will vary with the cell material quality, the temperature, and light intensity.

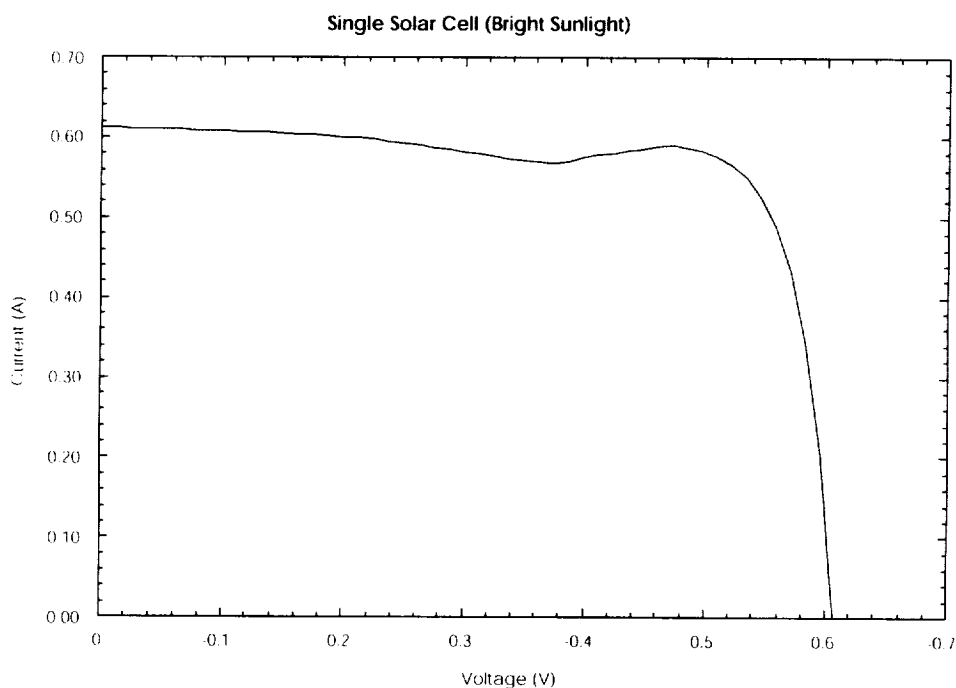


Figure 2 IV Curve for a 3.5 x 6 cm. Si Solar Cell

Solar cells are characterized by current and voltage measurements. All of these characteristics are dependent on the light intensity. A solar cell has its highest voltage when no load is applied and it is left open circuited; this is called the open circuit voltage or V_{oc} . Likewise, it has its highest current when the leads are shorted together; this is the short circuit current or I_{sc} . The solar cell cannot supply any power in either of these modes; the maximum power point is somewhere between the two extremes. A fourth parameter, known as the fill factor, defines the quality of the cell with an ideal at 100%. This is the ratio of the maximum power to the extreme power or $P_{MAX}/(V_{oc}I_{sc})$. The open circuit voltage for this array is 18 volts and the short circuit current is 1.8 amps. Typical Cell Parameters are shown in table 1.

V_{oc}	-.6076 V
I_{sc}	.6120 A
Fill Factor	79.3 %
V_{MAX}	-.52
I_{MAX}	.56 A
P_{MAX}	295 mW

Table 1 Solar Cell Parameters

The cells in the array are grouped into 3 strings of 30 cells each. The cells are connected with 18-gauge wire which is soldered to the cells. A picture of the solar cells and their wiring is shown in figure 3. Series cells are connected front to back and parallel cells are connected front-to-front and back-to-back. The 30 cells in each string are connected in parallel, comprising 3 parallel strings. The wing is 6 cells wide and 15 cells long so that each string runs up and back down the wing. The array-wiring diagram is shown in figure 4. Blocking diodes are added to each string to prevent current flow into adjacent strings if the voltages do not match due to shadowing. If string voltages do not match when they are connected in parallel, current will flow into the lower voltage string causing loss of power. Blocking diodes allow the current to flow out of but not into a string. The total array maximum output power is 22.5 watts (1.5 Amps at 15 volts). This power is an estimate under ideal weather and sun conditions, which would be near solar noon on a cloudless day.

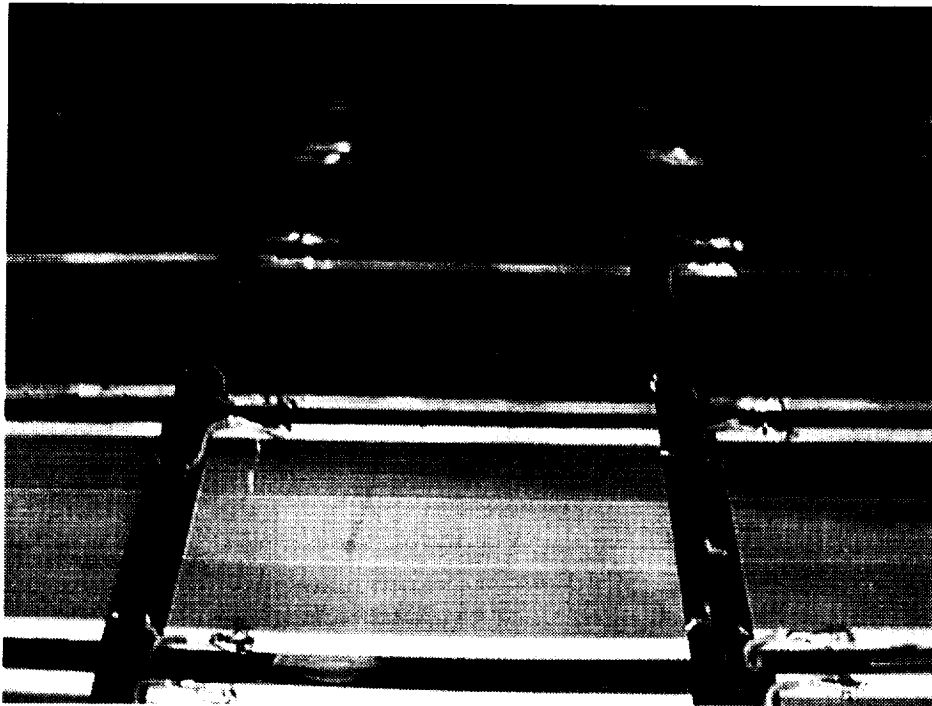


Figure 3 Solar Cells and Wiring

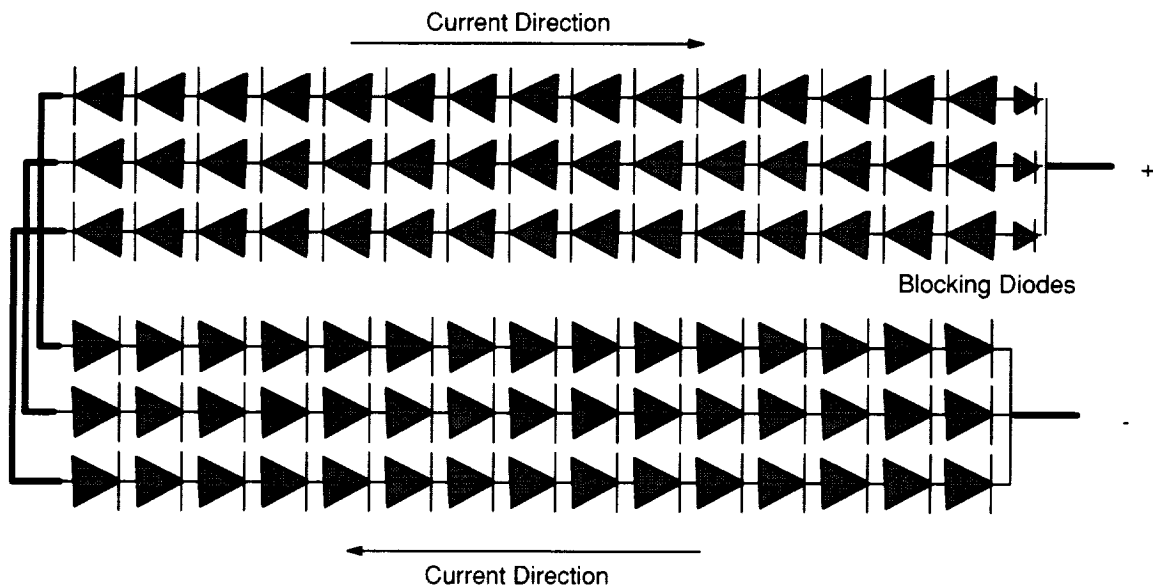


Figure 4 Array Wiring Diagram (30 x 3)

The solar cells are mounted in an airfoil shaped plastic wing section. This wing section is used to mimic the shape of an aircraft wing. It is mounted on a stand which allows it to rotate $\pm 90^\circ$ to vary the angle of the incoming solar radiation. A picture of the system including the wing section is shown in figure 5. The array angle is adjusted by loosening the knob on the side of the array and manually adjusting its position. A position indicator is attached to the stand. This indicator can be used to estimate the angle change

in the array. A picture of this adjustment mechanism is shown in figure 6. The output power of the array will vary with the cosine of the angle between the direct sun and the angle of the wing. For example if the wing were angled 60° off the sun, the power output would be 50% of the power compared with the array normal to the sun. A plane will most likely have varied sun angles throughout a flight. Variation in these angles will determine the power from the array. Flight path information is critical to sizing the array and battery required for a mission.

By experimenting with the wing tilt, battery power, and motor speed most of the variables of flying a solar plane can be studied. Although in practice the ability to safely fly a solar powered aircraft can become quite complicated and cannot be fully addressed by this system demonstrator.

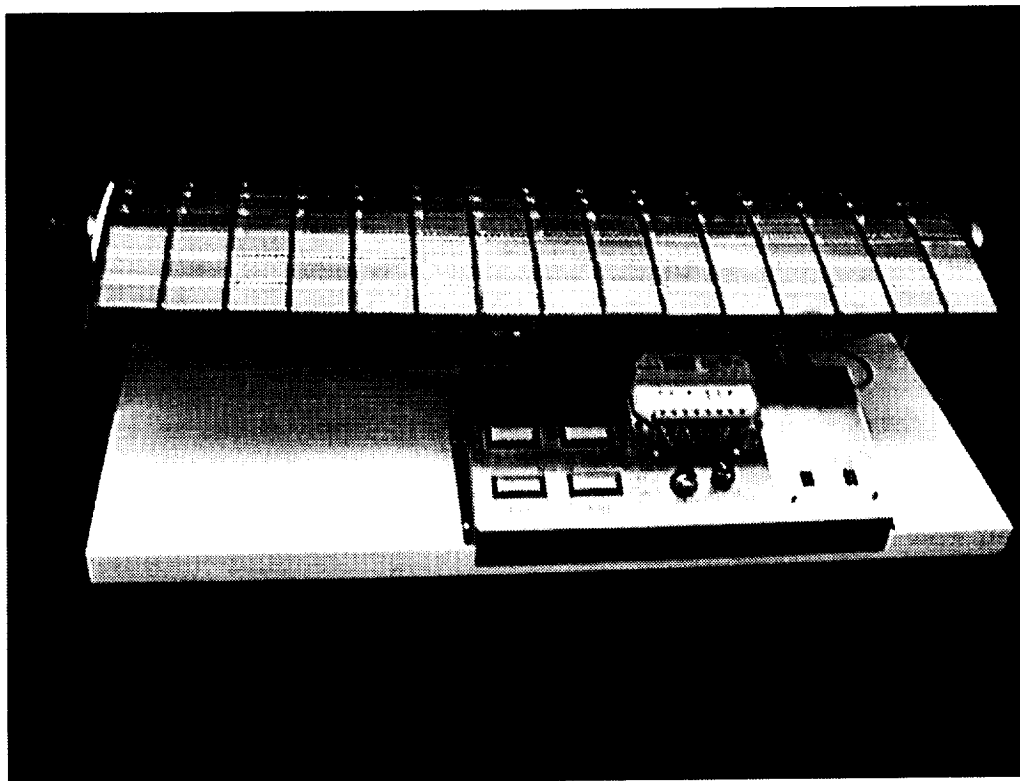


Figure 5 PV Array Wing Section

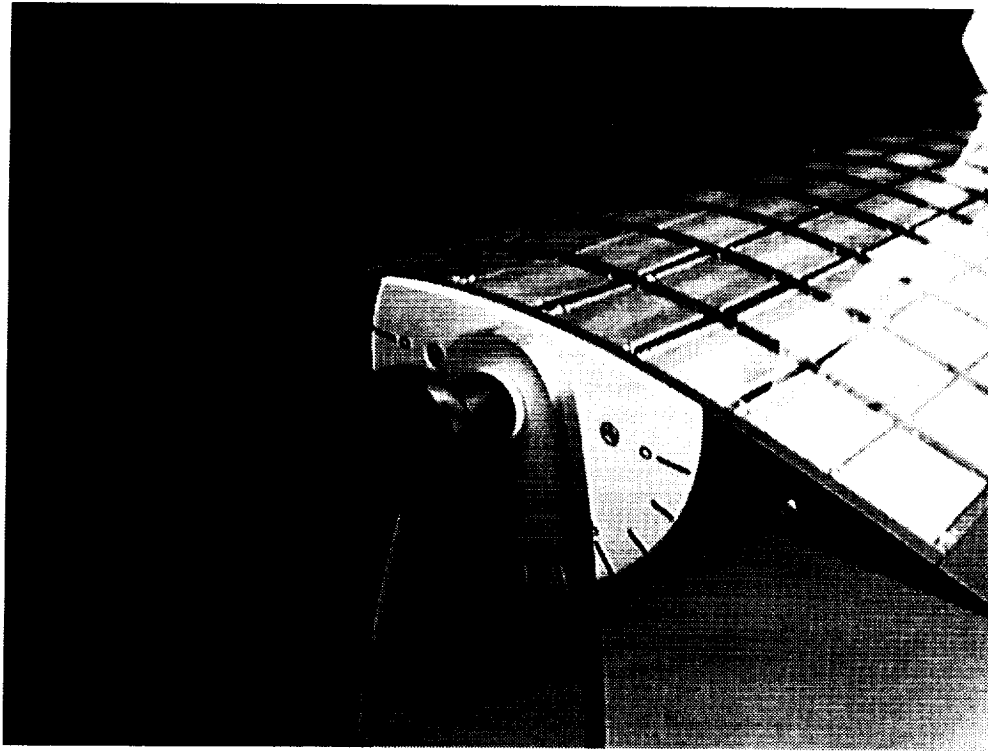


Figure 6 Wing Adjustments and Position Indicator

Battery

The battery included in the system is used to supply power to the motor when there is insufficient power being produced by the solar array. This can occur due to either high demand by the electric motor, beyond the capability of the array, or a decrease in the incoming solar energy caused by a cloud or other event.

The battery used in the system is a Panasonic (LCR122R2PU) sealed, rechargeable lead acid battery with a capacity of 2.2 amp hours. The battery operates at a voltage of 12 volts and has a maximum discharge current of 20 amps. The battery is mounted to the base of the stand and is connected to the system through the battery charge controller which regulates the charge / discharge rate for the battery.

Battery selection is also a critical part of the power system. Battery size, weight, and capacity all must be considered when choosing a battery. Another parameter is charging capability. Lead acid batteries prefer shallow cycles, where they don't drain much of the battery's total power. Nickel cadmium batteries should be deep cycled, where they are nearly discharged when used. A photo of the battery mounted to the array base is shown in figure 7. Orientation of the battery does not affect performance, however it does contain acid and one should be careful of heat and leakage. These batteries may be damaged if connected in reverse.

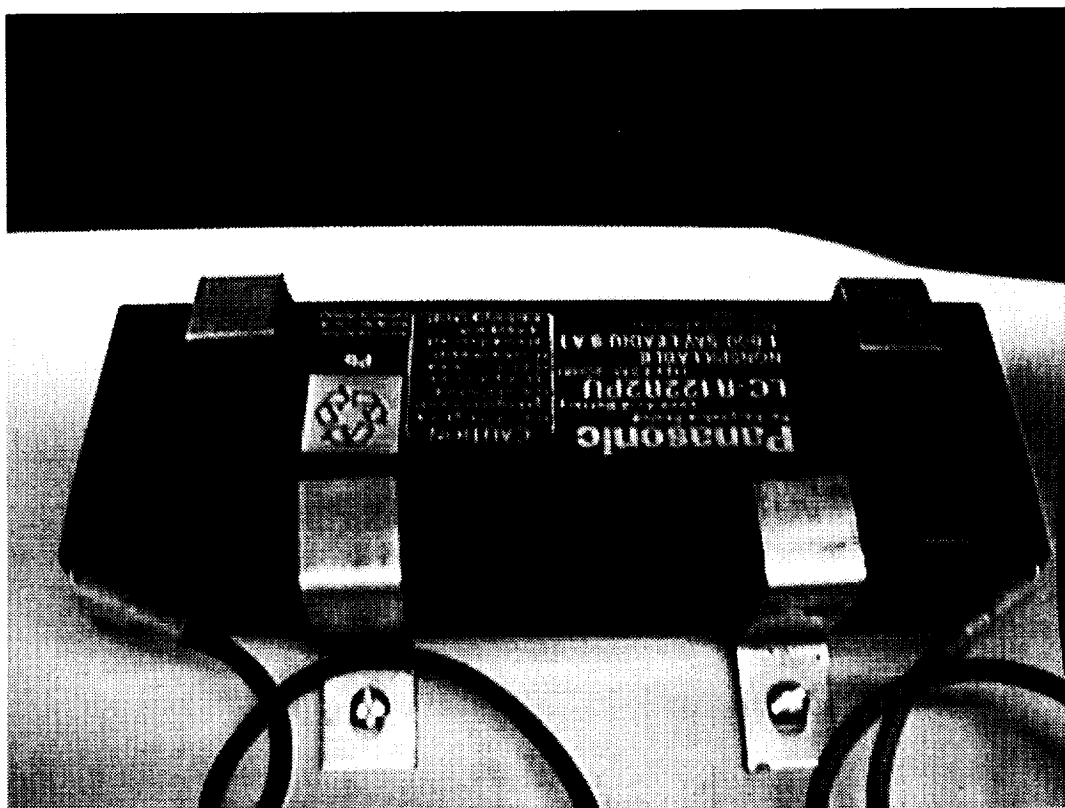


Figure 7 Battery Mounted onto the Base

Control Panel

The control panel used on the system is the main control and display point of the system. A photograph of the control panel is shown in figure 8. An overall diagram of the wiring of the control panel is shown in figure 9. The control panel is made of stainless steel and houses the following items:

- All the electronic components of the system (battery charge controller, wiring and motor controller)
- Panel meters, which are used to display the present operational status of the system, including all voltages and currents
- Operational controls (On / Off switch for the array, battery, motor and meters plus a motor speed control).

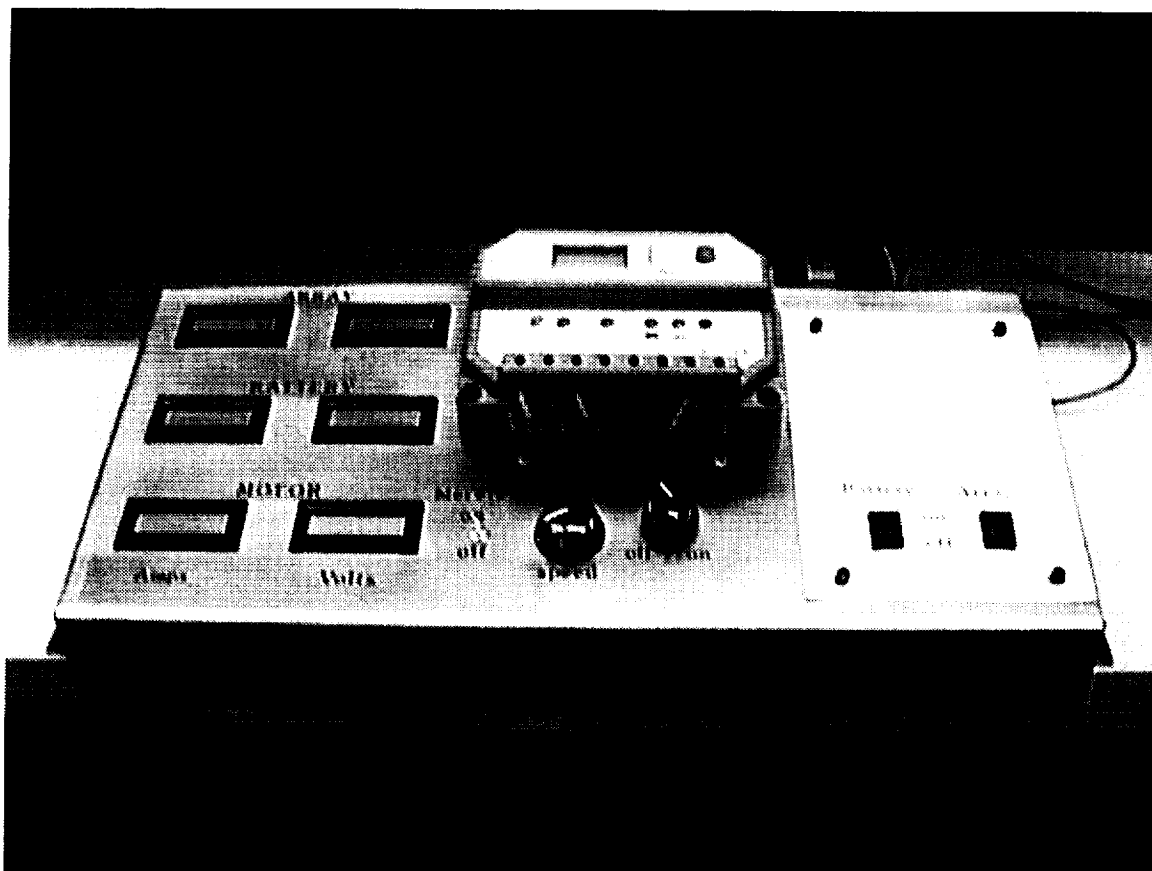


Figure 8 System Control Panel

The control panel is the main junction point for the array, battery and load (electric motor and propeller). Each of these components plugs into the back of the control panel and all subsequent system wiring is housed within the control panel. The system is self-contained, requiring no outside power source for operation. The array power is connected to the battery charge controller as well as directly to the motor controller. The output of the charge controller is also connected to the motor controller. This arrangement allows the array to power the load completely under low power situations and both the array and battery to jointly power the load under high power situations. A blocking diode was used to insure that current from the battery did not flow back to the array.

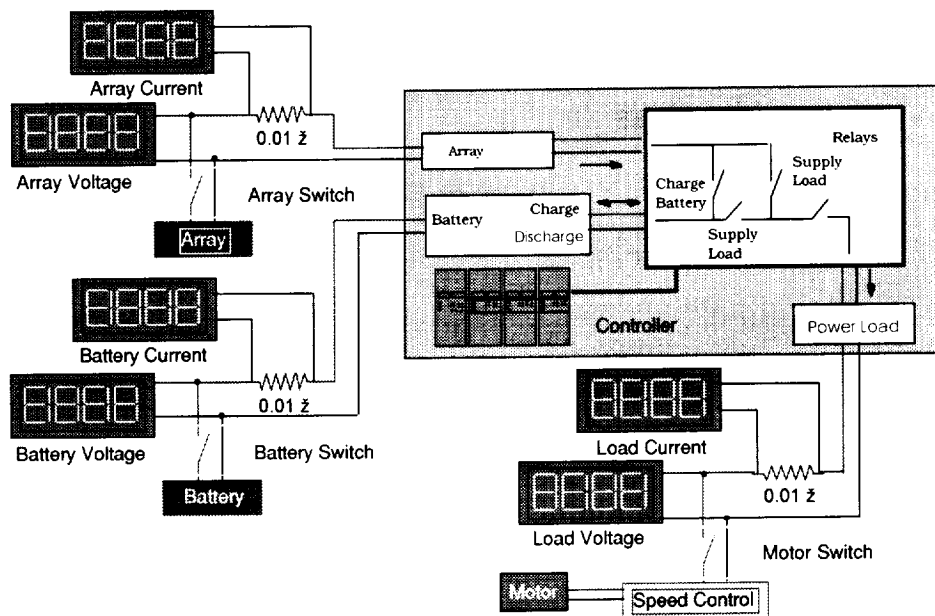


Figure 9 Control Panel Wiring Diagram

Battery Charge Controller (Power Management)

The battery charge controller used is a ProStar 12 manufactured by Morningstar¹. The controller regulates the current going to the battery to maintain a constant state of charge for the battery. The controller determines this state of charge by monitoring the battery voltage. The controller also determines the rate of charge on the battery, the optimum distribution of power from the array to the load and battery. This controller also shuts down the load if the battery drops below 8 volts. This controller is shown in figure 10. The controller was designed for a terrestrial application on a 12 V system. It would have to be modified to control an airplane. The main issue with using this controller in an aircraft power system is the time lag, which occurs during recharge of the battery. There is a 2 to 5 minute delay between when the charge is turned on and charging of the battery will begin. It has a microprocessor control and monitors the voltages and currents of the array, battery and load to determine how the power is distributed. This is updated once a second.



Figure 10 Battery Charge Controller

Power leads from the array output, battery and motor controller are connected to the battery charge controller. The battery output is not directly connected to the motor controller; all current in or out of the battery passes through the battery charge controller. Information on the operation of the battery charge controller can be found in Reference 1.

Motor Controller

The electronic motor controller is used to turn the electric motor on or off as well as to change its rpm by adjusting current flow to the motor. The motor controller is wired directly to the array and to the battery through the battery charge controller. The controller is a simple dashpot type current adjuster with a switch to open the circuit to the motor.

The speed of the motor is varied by pulse width modulation or PWM. This means that the motor is switched on and off, or pulsed, while maintaining the voltage at 12 V. Very short pulses provide little power to the motor and therefore slower speeds. Longer pulses increase the power and speed. The pulses are spaced very close together so that the motor doesn't get a chance to stop. The added advantage of PWM is that the voltage is maintained, providing higher torque even with low speed.

Display Meters

A series of meters are on the control panel to display the current and voltage levels from the array and battery, and to the electric motor. The meters are Acculex LCD digital meters model DP650 (± 200 mV), used for the current display, and model DP654 (± 20 V), used for the voltage display. The meters are arranged in a column with the current display for each component on the left and the voltage display on the right. The meters require a 5-volt source to run. This was supplied by an independent DC/DC supply off the 12V battery mounted within the control panel. The voltage meters measure the voltage at the connection of the components to the control panel. The current meters read the voltage drop across a .01-ohm resistor placed in the positive lead line of each component being measured.

The meters provide a way to view the power being drawn or supplied by all the components. The direction of the current can be determined by the sign on the meter, i.e. positive battery current means the battery is providing power to the load and negative current indicates it is being charged. The voltage shows the health of the components, all being optimized for a 12 V system.

Electric Motor and Propeller

In order to supply a load to the system, an electric motor driving a propeller is used. This type of load was selected since it is representative of the power system load for a solar electric aircraft. Also, it provides a good visual demonstration of the effect that variations in incoming solar energy have on the system performance. The motor used is a Graupner 500E 12-volt DC electric motor. The motor specifications are given in table 2.

A propeller is used in conjunction with the motor to supply resistance during operation. The propeller used is a J Z A zinger 14 x 8. For protection the propeller was housed in a screened propeller enclosure. A photo of the enclosure is shown in figure 11 and a photo of the electric motor mounted to the propeller enclosure is shown in figure 12. The power from the motor and propeller can be quite high, avoid coming in contact with the moving blades.

Nominal Voltage	12 V
Operational Voltage Range	6 to 12 V
No - Load Speed	12,000 RPM
Idle Current Drain	0.4 A
Current Drain at Maximum Efficiency	2 A
Blocking Current Drain	10 A
Maximum Efficiency	67%

Table 2 Graupner 500E Electric Motor Specifications

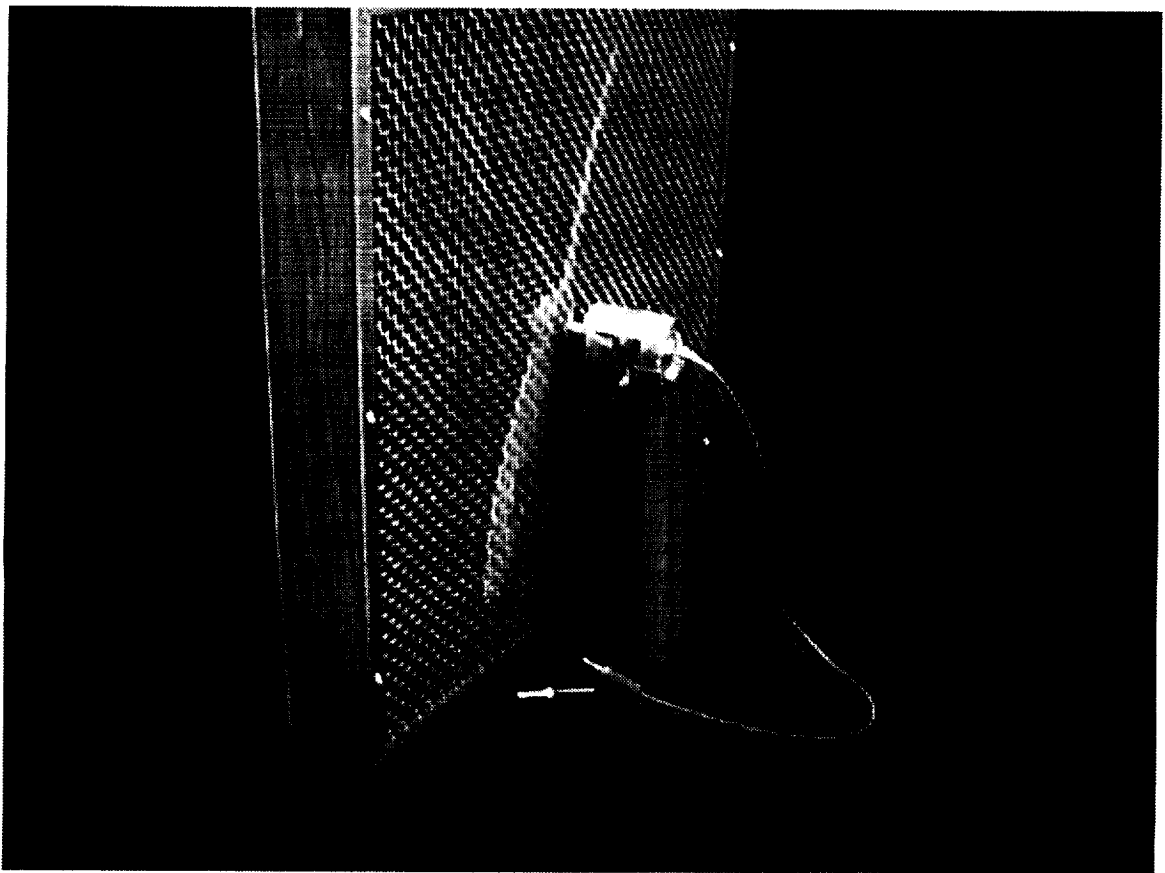


Figure 11 Screened Propeller Enclosure

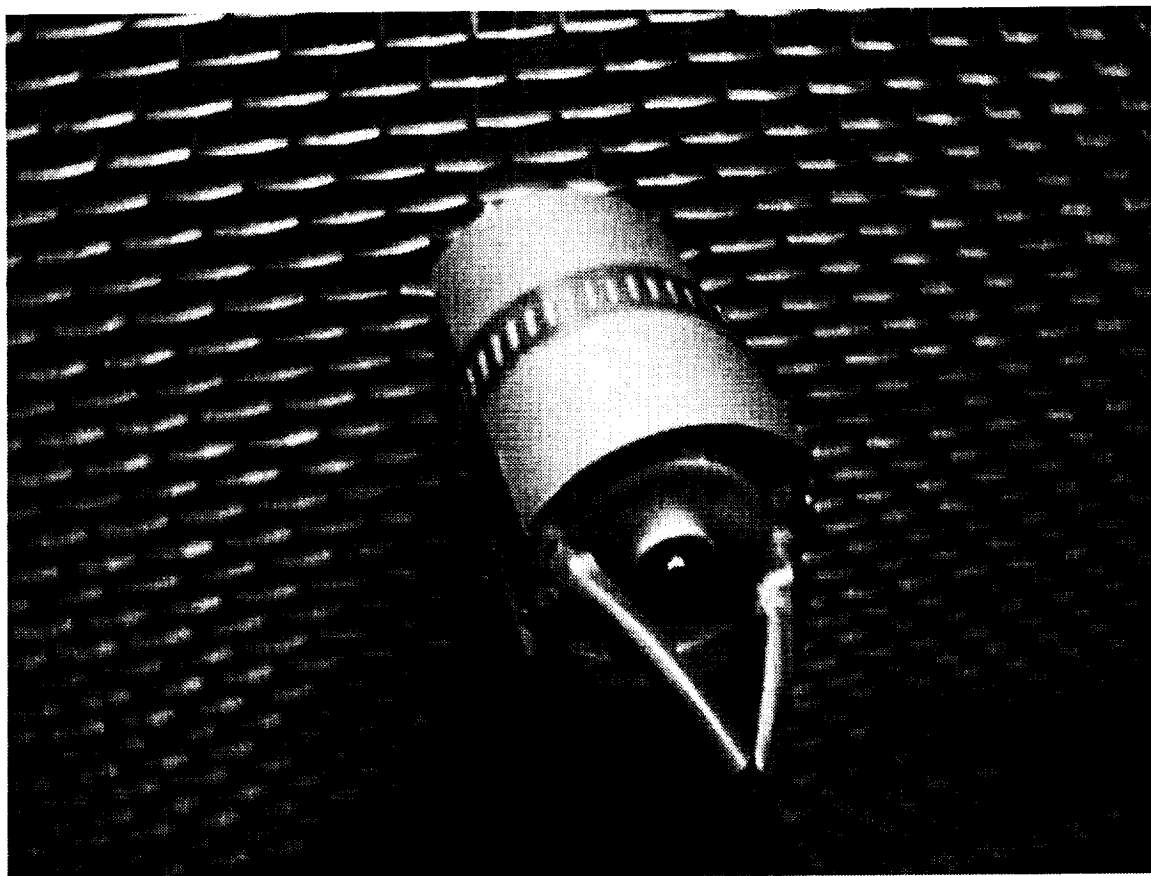


Figure 12 Electric Motor

System Operation

The following section summarizes the setup and operation of the system. This includes a step-by-step procedure for getting the system up and running, an explanation of the operation and total capabilities of each of the component's controls and a troubleshooting guide in case the system does not function properly.

Setup

The array and control panel are permanently mounted to the base stand. To set up the system, first position the aircraft wing so that there are no obstructions between it and the incoming sun light. Then adjust the array angle to the desired position and connect the array, battery and electric motor to the rear of the control panel. The connectors at the rear of the control panel are marked to indicate where each device is to be plugged. The plugs and connection wires are color coded, red for the positive leads and black for the negative or ground leads. The connection wires use banana plugs, which are inserted into the connectors on each device and on the control panel. Figure 13 shows the connection wires attached to the solar array.

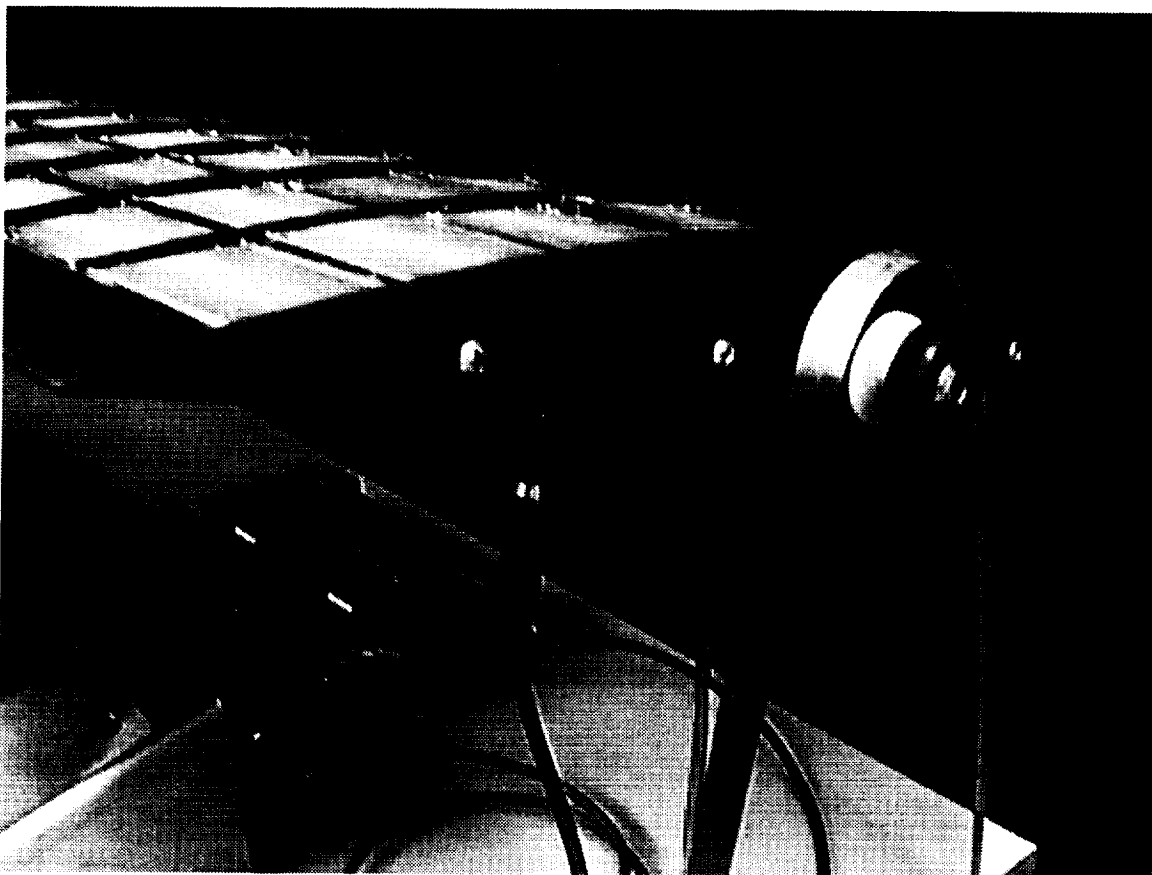


Figure 13 Solar Array Electrical Connection

Once the connection wires are in place the electric motor stand should be positioned to be visible but not in the way of the controls or shadowing the solar array. This completes the setup of the system. Note: it is important not to shadow any of the solar cells because each string of cells connected in series will produce an output current equal to that of the cell in the string producing the least current. Therefore by shadowing one cell a whole string can be effectively shut off.

Operation

The following is the operation procedure for the system:

- Turn the array switch to the on position. (shown in figure 14)
- Turn the battery switch to the on position. (shown in figure 14) The battery charge controller should start up at this point.
- Turn the meter switch to the on position. (shown in figure 15)
- Turn the motor switch to the on position. (shown in figure 15)
- Adjust the speed of the motor with the speed control knob. (shown in figure 15)
- Check the meters to see what the current and voltage is for each component of the system.

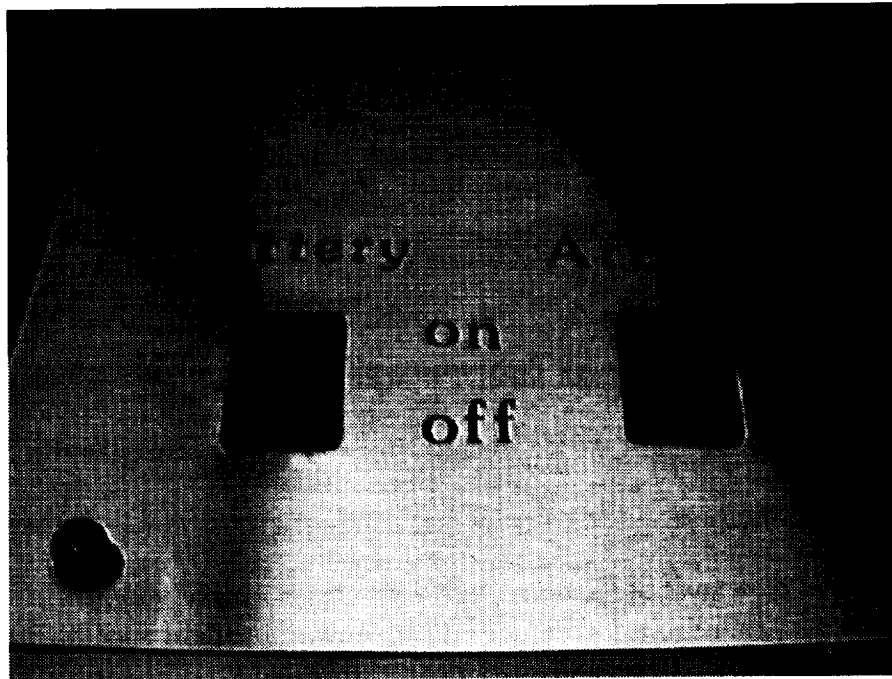


Figure 14 Power Switch for Array and Battery

To shut the system down follow the start up procedure in reverse order, moving all of the switch positions to the off position.

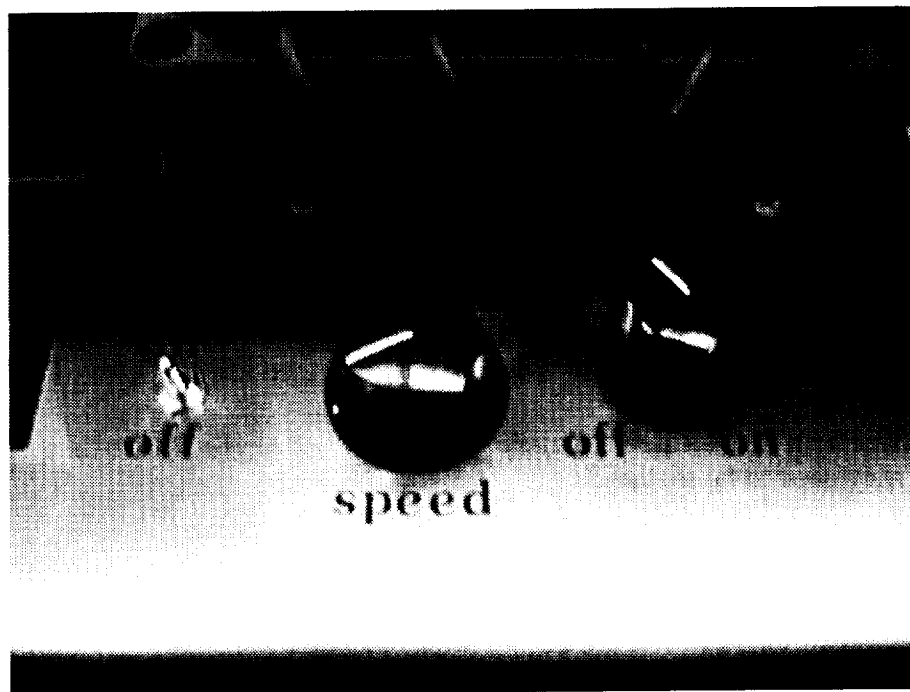


Figure 15 Motor Controls and Meter Switch

The battery charge controller has an automated procedure for its operation. Upon being power up it will go through a start up sequence, assessing the state of charge of the battery. Because of this procedure there is a 2 to 5 minute delay before charging of the battery will begin. If the battery voltage is low and there is sufficient power from the solar array it will begin to charge the battery. The battery charge controller has a number of manually activated indicators, which show the present state of operation. The operation of the controls on the battery charge controller are given in Reference 1.

Troubleshooting

If the motor does not operate check the following items:

1. Check to make sure the On-Off switches for the array, battery and motor are turned on.
2. Make sure the motor speed adjustment is turned sufficiently clockwise to start the motor.
3. Check the voltage level of the array. If the voltage is zero or very low:
 - Check the connections to both the components and control panel to make sure they are securely connected.
 - Check to make sure nothing is shadowing the solar array and make sure there is direct sunlight falling on the array.
4. Check the voltage level of the battery. If the voltage is zero or very low:
 - Leave the array on and turn the electric motor and display panel off until the battery has been charged and its voltage has returned to 12V or greater (remember it may take up to 5 minutes before the charge controller begins to charge the battery).
 - If after a few hours the battery voltage has not begun to rise then the battery may need to be replaced.

If the display meters do not operate check the following items.

- 1 Make sure the meter power on switch is in the On position.
- 2 Use a voltmeter to check the voltage level of the battery.
 - If the battery voltage is zero or very low turn the array and battery on, leave the electric motor and display panel off and let the battery recharge (remember it may take up to 5 minutes before the charge controller begins to charge the battery).
 - If after a few hours the battery voltage has not begun to rise then the battery may need to be replaced.

Reference

1. Morningstar Corporation: ProStar Photovoltaic System Controllers Operator's Manual. April 1996.

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